Frequency locking to a high-finesse Fabry-Perot cavity of a frequency doubled Nd:YAG laser used as the optical phase modulator

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Abstract

We report on the frequency locking of a frequency doubled Nd:YAG laser to a 45 000 finesse, 87-cm-long, Fabry-Perot cavity using a modified form of the Pound-Drever-Hall technique. Necessary signals, such as light phase modulation and frequency correction feedback, are fed direcly to the infrared pump laser. This is sufficient to achieve a stable locking of the 532 nm visible beam to the cavity, also showing that the doubling process does not degrade laser performances.

1 Introduction

The use of high finesse Fabry-Perot (FP) cavities has become widespread in the last decade, especially due to the availability of very high reflectivity mirrors. FP resonators play a crucial role in several physical fields, such as QED and vacuum structure measurements with optical techniques[1], gravitational wave detection with interferometers[2] and resonant bars[3], and metrology. Their use for H^0 stripping in high intensity proton drivers with H^- injection has recently been suggested[4]. The resonant operating condition of these devices is achieved by frequency locking a laser to one of the fundamental modes of the cavity. The Pound-Drever-Hall technique[5] is the most common method used to accomplish such a locking: the cavity instantaneous frequency is sensed by putting frequency-modulation (FM) sidebands on the cavity input beam, and a correction signal is then extracted and applied to change accordingly the laser frequency. Tuneable lasers have proved to be the best suited to implement such a scheme, and the Non Planar Ring Oscillator (NPRO) solid state diode-pumped Nd:YAG laser is probably the most common type of laser used in such applications. This device allows for two different types of modulation: a "slow" one (bandwidth $\sim$ 1 Hz, dynamic range of several GHz), and a "fast" one (bandwidth $\sim$ 100 kHz, dynamic range $\sim$ 200 MHz). Our group has developed an original locking scheme, in which FM sidebands at frequencies $>$ 500 kHz are generated using the laser itself, and the method was succesfully applied to a Nd:YAG laser emitting at 1064 nm[6]. In several applications, such as PVLAS type[1] measurements and H^- double stripping[4], there is an added bonus when operating at shorter wavelengths.

The frequency doubled version of the above mentioned laser has become available only recently. In this device the infrared (IR) beam exiting the Nd:YAG crystal is fed onto a doubling crystal, where, under specific conditions, a second beam is generated at twice the original frequency. The output beam is a green radiation ($\lambda =$ 532 nm), having spectral characteristics which closely match those of the IR pump beam. In this paper we will show that it is possible to achieve frequency locking of the doubled beam with the same good results already obtained with the IR beam output by a Nd:YAG laser. In particular, we show that it is possible to generate the FM sidebands on the green output without using an external phase modulator.

2 Method

The frequency doubled NPRO laser[7] is a tuneable laser emitting at 532 nm. The green output is generated by a single passage of the IR beam, coming from an NPRO Nd:YAG source, inside a periodically poled KTP (PP KTP) crystal kept at a stable temperature, so as to guarantee the correct phase matching for second harmonic generation. Tuneability is achieved by changing the frequency of the pump laser by means of a temperature control of the NPRO crystal (Bandwidth $\sim$ 1 Hz, Dynamic range $\sim$ 60 GHz), or of a piezoelectric transducer (Bandwidth $\sim$ 100 kHz, Dynamic range $\sim$ 200 MHz) mechanically acting on the laser crystal. In order to have the widest possible dynamic range it is compulsory to use single passage second harmonic generation. This enhances stability in the intensity of the green output, but results in a lower output power.

As shown by Cantatore *et al.*[6], phase modulation is equivalent to frequency modulation. This allows for the possibility of using the laser itself as the optical phase modulator. The phase φ of a phase-modulated beam can be written as:

$$\varphi(t) = \omega_0 t + \beta \sin(\Omega_m t + \psi) \tag{1}$$

where ω_0 is the laser angular frequency, Ω_m is the angular frequency of modulation and β is the modulation index. In our setup we are using the piezoelectric actuator on the laser head for simultaneous frequency correction and phase modulation.

3 Apparatus

A schematic drawing of the apparatus is shown in figure 1. The laser emits a 100 mW, 532 nm, visible light beam, which is mode matched to the TEM_{00} mode of a Fabry-Perot cavity by means of a lens. The cavity is 87 cm long and is kept under vacuum (total pressure $\leq 10^{-5}$ mbar); beam input to the vacuum enclosure is possible through glass windows. The mirrors forming the FP cavity are high reflectivity dielectric mirrors[8] with an expected reflectivity of 0.99997. The feedback amplifier is a four-stage integrator circuit with a unity gain point that can be chosen in the 20 - 50 kHz interval: its transfer function has three poles in the origin and one at 0.16 Hz, and the 24 dB/octave slope begins below 7 kHz. A more detailed description of the feedback system can be found in Ref. 6. The correction signal coming from the feedback amplifier is summed to the phase-modulation signal and fed into the laser frequency tuning input. The possible bandwidth of the feedback

loop is limited to the region of linear behaviour of the laser piezoelectric (PZT) actuator ($\sim$ 100 kHz), where it has an actuation coefficient of $\sim$ 2 MHz/V (for the green light output). For larger modulation frequencies the response is no longer linear, however the PZT can still be used at a fixed frequency for phase modulation. In order to reduce the unwanted Residual Amplitude Modulation (RAM) introduced by the phase modulation, one has first to study the modulation characteristics of the laser. In fact, as can be seen from figure 2, the RAM in the output beam changes with the frequency of the phase modulation signal. A RAM in the beam intensity produces a constant frequency shift between the laser and the Fabry-Perot cavity. The working frequency is then best set to the value where the RAM reaches a minimum. Accordingly, the modulation depth for several values of the modulation frequency has been measured, and the results are summarized in table 1. As can be seen from figure 3 the index of modulation β (see Eq. 1) is linear with the voltage V_{p} applied to the laser PZT. In addition, we have also found that the ratio RAM/β results to be constant as a function of V_{p}. In the region around 660 kHz the RAM has a minimum value, with a ratio RAM/β of the order $\sim 1 \times 10^{-4}$. This value is about three times larger than the value found[6] using the infrared output of an NPRO laser (Lightwave model 124). The difference can probably be explained by the second harmonic generation process. In order to achieve the deepest modulation with minimum RAM, the working frequency has been chosen at $\Omega_{\mathrm{m}}/2\pi = 660$ kHz.

4 Results

The green laser output was successfully locked to the FP cavity. A cavity transmission of 7 % was obtained and the measured finesse was 45 000. The frequency locking was stable for durations up to several hours. Figure 4 shows the spectral density of the difference between the laser frequency and the instantaneous resonance frequency of the cavity. This spectral density has an overall minimum value of $\sim$1 mHz/$\sqrt{\mathrm{Hz}}$, while it stays below 10 mHz/$\sqrt{\mathrm{Hz}}$ in the region 1-200 Hz (excluding peaks due to the 50 Hz mains frequency and its harmonics). This result is comparable again to the one obtained using the IR output of the NPRO laser. The estimated value of the frequency shift due to RAM is $\sim$ 0.1 Hz. Finally, table 2 below summarizes a few relevant characteristics and measured performances of the system.

5 Conclusions

It has been shown that it is possible to lock the green output of a doubled IR NPRO laser to a resonant, high-finesse, Fabry Perot cavity, using an originally modified form of the Pound-Drever-Hall technique. In particular, phase modulation of the beam was achieved using the piezoelectric transducer acting on the infrared pump laser crystal. This allows for a simple locking scheme involving a previously unavailable wavelength (532 nm in this case), which is now in the visible domain.

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FIGURE CAPTIONS

Figure 1: Experimental set-up.

Figure 2: Residual amplitude modulation (RAM) as a function of the modulation frequency. The signal on the PZT has an amplitude of 48 $\mathrm{mV_{pp}}$.

Figure 3: Index of modulation versus the voltage V_{p} applied to the piezoelectric transducer at the chosen modulation frequency of 660 kHz.

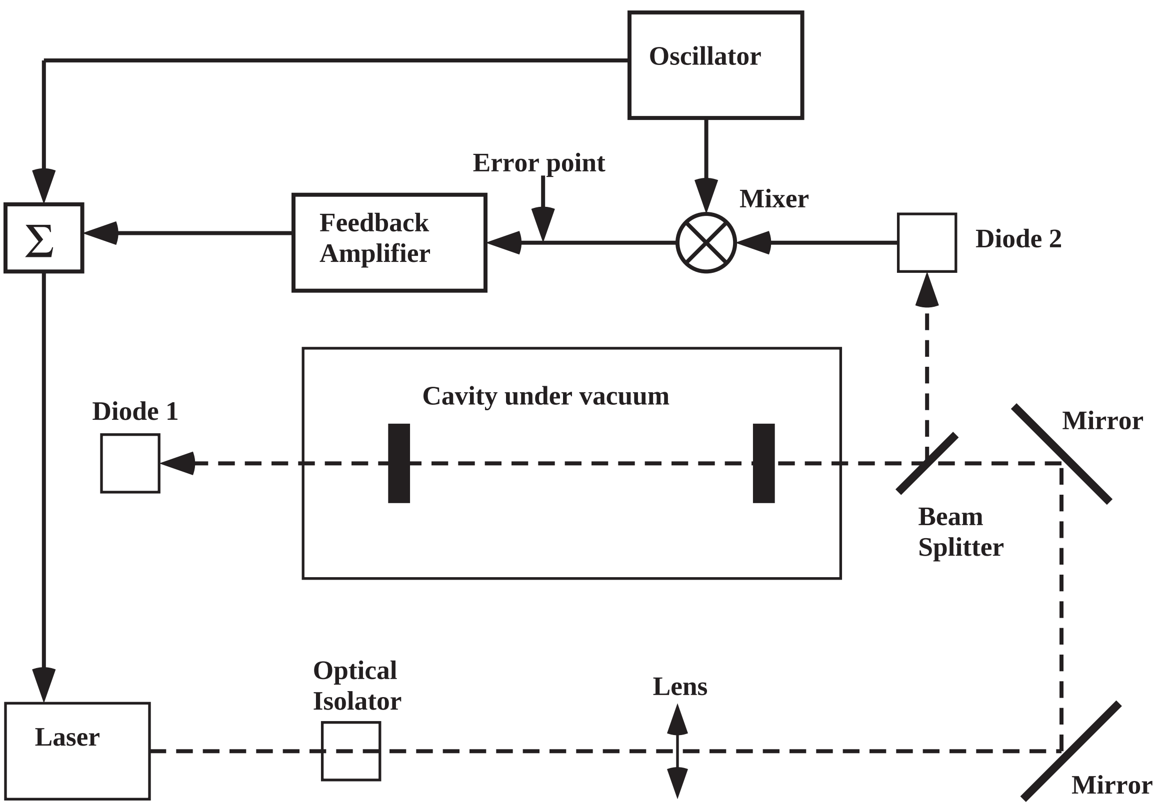
Figure 4: Spectral density of the difference between the laser frequency and the resonance frequency of the cavity. This is obtained by measuring the noise spectrum at the error point of figure 1 and by multiplying it by the slope of the error signal in the same point. The large peaks are due to 50 Hz and its harmonics.

Table 1: RAM and β as a function of the voltage applied to the PZT for some values of the frequency.

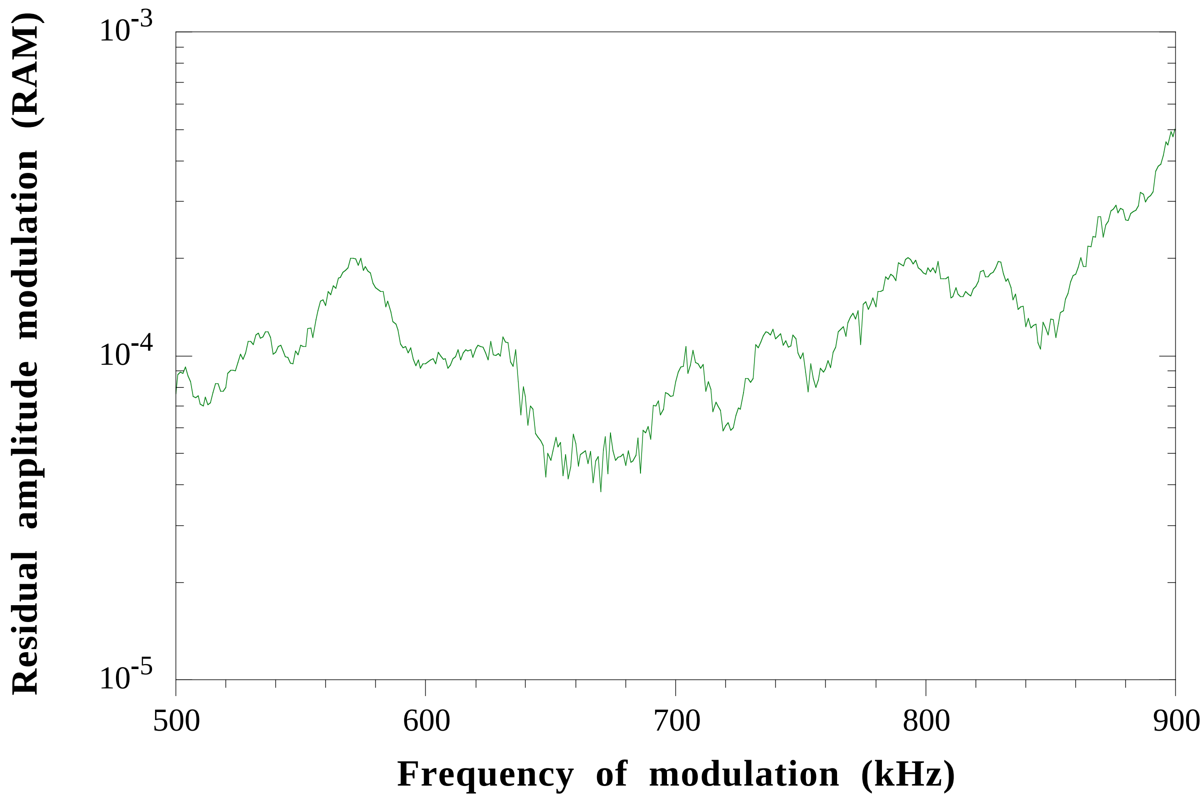
ν (kHz)	V_{pp}/β (mV)	RAM/V_{pp} (mV^{-1})	RAM/β
600	109	1.97×10^{-6}	2.15×10^{-4}
660	100	1.12×10^{-6}	1.12×10^{-4}
733	104	2.21×10^{-6}	2.31×10^{-4}
830	163	4.06×10^{-6}	6.60×10^{-4}
900	93	1.06×10^{-5}	9.84×10^{-4}

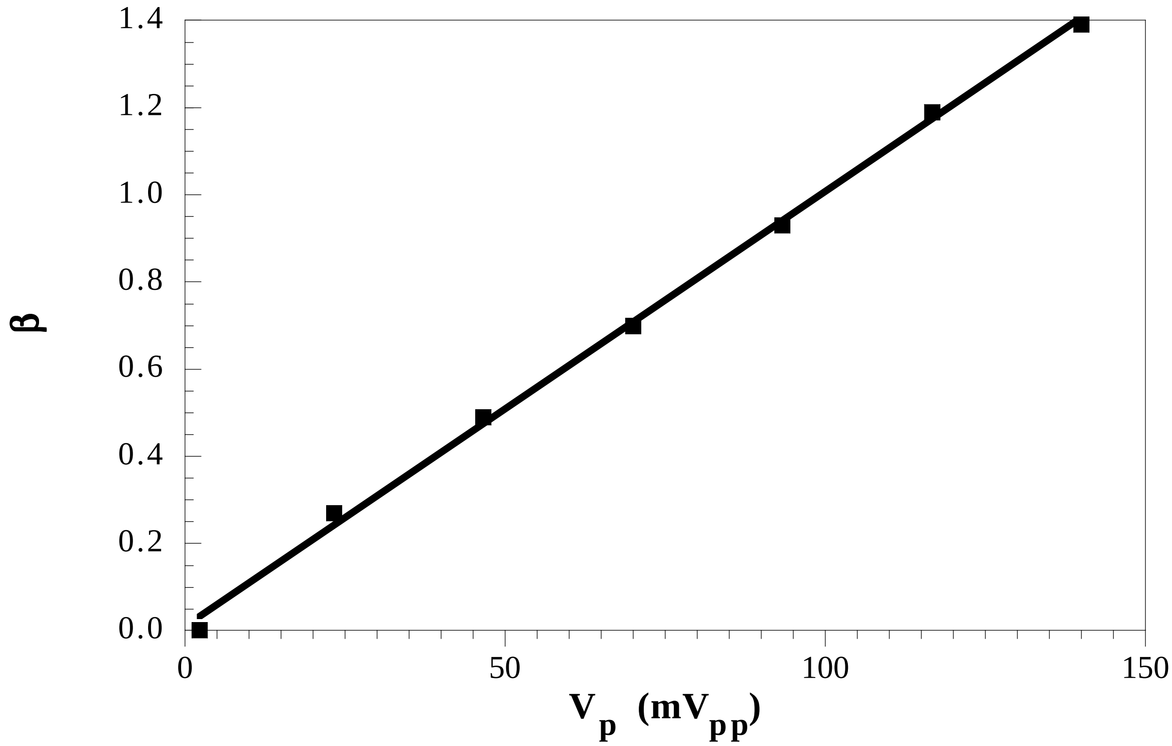
Table 2: Summary of relevant system characteristics and measured performances

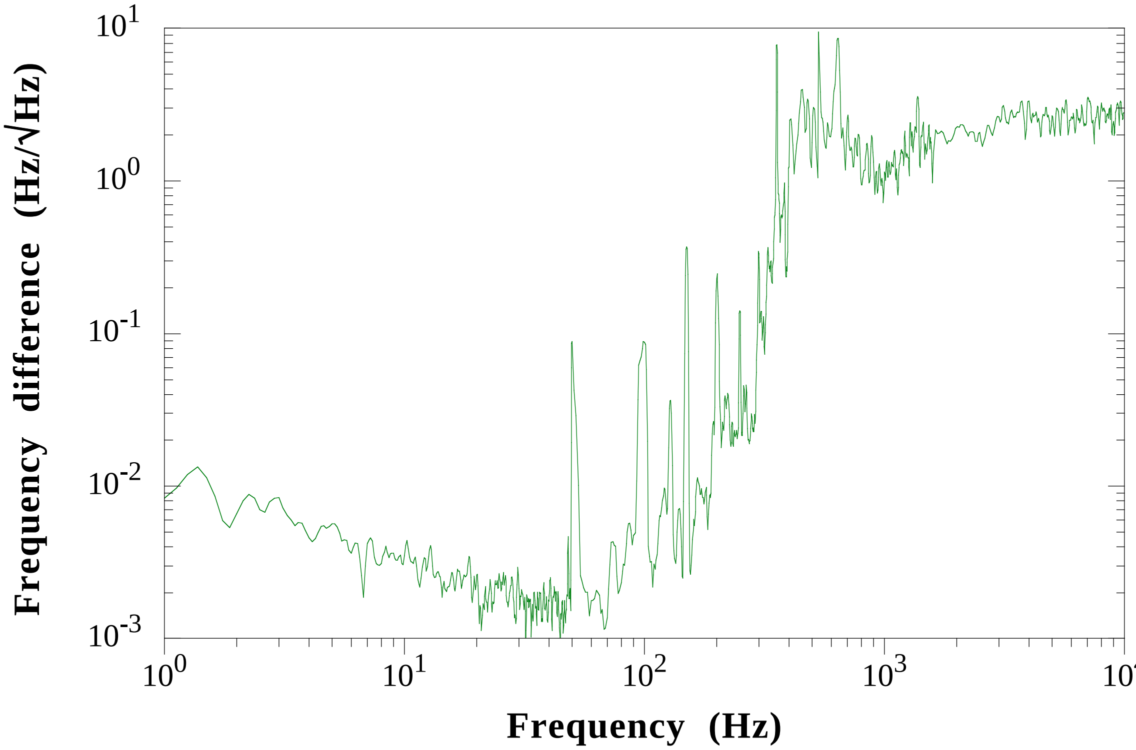
laser wavelength	532 nm
laser output power @532 nm	100 mW
FP cavity length	87 cm
FP cavity finesse	45000
FP cavity Q factor	1.4×10^{11}
beam waist at cavity center	0.7 mm
light power density at cavity center	120 W/cm^2
energy stored in the cavity	50 nJ
NPRO temperature control BW	1 Hz
NPRO temperature control dynamic range	60 GHz
NPRO PZT control BW	100 kHz
NPRO PZT control dynamic range	200 MHz



Oscillator
Error point
Mixer
Feedback
Amplifier
Σ
Diode 2
Cavity under vacuum
Diode 1
Mirror
Beam
Splitter
Optical
Isolator
Lens
Laser
Mirror


Residual amplitude modulation (RAM)
10-3
10-4
10-5
500
600
700
800
900
Frequency of modulation (kHz)


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
β
0
50
100
150
V_p (mV_{pp})



Frequency difference (Hz/√Hz)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)